AIAA-98-4731

MDO TECHNOLOGY NEEDS IN AEROELASTIC STRUCTURAL DESIGN

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Abstract

Increasing performance requirements and economical pressure to reduce aircraft Direct Operational Costs can no longer be met by traditional design processes. In particular, the impact of aeroelastic effects on aircraft design demands the use of multidisciplinary design concepts and optimization (MDO) strategies to develop flutter-free structures and to ensure excellent multipoint performance characteristics. This paper describes the aeroelastic and aeroservoelastic MDO problem, presents a variety of production and research level methods for its solution, and highlights current bottlenecks. Industrial MDO technology needs for aeroelastic structural design are identified by reviewing previous aeroelastic studies performed at Daimler-Benz Aerospace AG Military Aircraft Division (DASA-M) and results from a study in which several DASA-M staff members were asked to specify future analysis and MDO needs. A trend towards loosely coupled approaches is detected which is opposed by a current shortage of framework software and MDO algorithms specifically supporting industrial implementation and use. Another obstacle is the lack of standardized tool interfaces. Finally, cultural changes are required in industry to exploit the full potential of MDO.

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General Aeroelastic Requirements for High Performance Aircraft Design

The whole spectrum of aeroelastic phenomena to be considered during the design process can be classified by means of Collar's well-known aeroelastic triangle of forces illustrated in Fig. 1. Three types of forces - aerodynamic, elastic and inertial - are involved in the aeroelastic process. Generally aeroelastic phenomena can be divided in two main groups:

- static aeroelastic phenomena, which lie outside of the triangle, i.e. divergence of the structure, control effectiveness, and load distribution created by aerodynamic and elastic forces, flight mechanic stability.
- dynamic aeroelastic phenomena, which lie within the triangle since they involve all three types of forces, i.e. flutter, buffeting, and dynamic response or dynamic flight stability.

All of these aeroelastic phenomena have profound effects on the aircraft design and can only be solved in concurrent consideration by all disciplines involved.

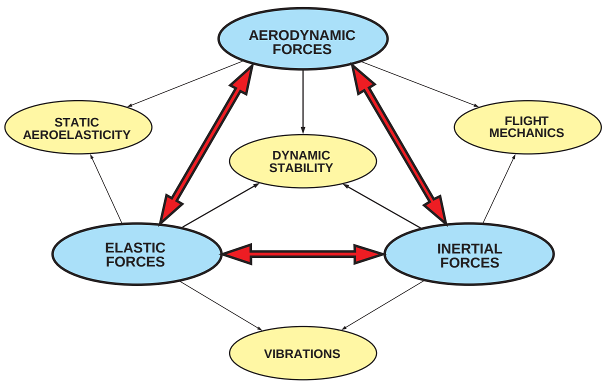

Fig. 1: Collar's Aeroelastic Triangle

The flexibility of the aircraft structure is fundamentally responsible for a variety of aeroelastic phenomena and related problems. As long as the strength requirements are fulfilled, structural flexibility itself is not necessarily objectionable. The aeroelastic deformations, however, may not only strongly influence the structural dynamics and flight stability, but also the overall performance and controllability of the aircraft. Therefore in the conceptual and preliminary design phase of a new aircraft, the application of aeroelastic design criteria becomes imperative for the structural design and optimization process. The following design criteria, among others, become the standard for any aircraft design:

- The aircraft must be free of flutter, divergence, and aeroelastic instability within its flight envelope
- the control effectiveness must be above a given minimum to assure safe flight performance within the flight envelope
- the flight shape of the wing should have minimum aerodynamic drag and sufficient effectiveness for all configurations.

Despite all these design criteria in a wide range of applications the airframe design process traditionally starts with a strength design and interactions with any control system are not considered in early design phases. Aeroelastic design criteria, however, are related to flexibility. Flutter stability of strength-designed metallic wing structures therefore must often be ensured with a non optimal repair solution. During the repair process, areas on selected components like spars or attachments with beneficial impact on flutter damping are identified and reinforced. This can be accomplished by analyzing the sensitivity of stiffness and mode shapes to reinforcement[1], as shown in Fig. 2. Nodal lines of the critical modes are moved, and the flutter speed increases (Fig. 3). Only small changes to the existing design are necessary, but a weight penalty is always added - in this particular case 95 kg.

Concurrent consideration of stress and flutter constraints in a complete re-design, as demonstrated in a recent European research project on MDO[2] („MDO-Project“), has the potential to yield a feasible design with a smaller weight increase. To achieve this goal, symmetric and antimetric boundary need to be regarded simultaneously. A large number of structural optimization tools, however, do not permit this approach. As a result, full models must be used, which may render the design problem too large to handle [3].

Fig. 2: Results of Sensitivity Analysis (Ref. 1)

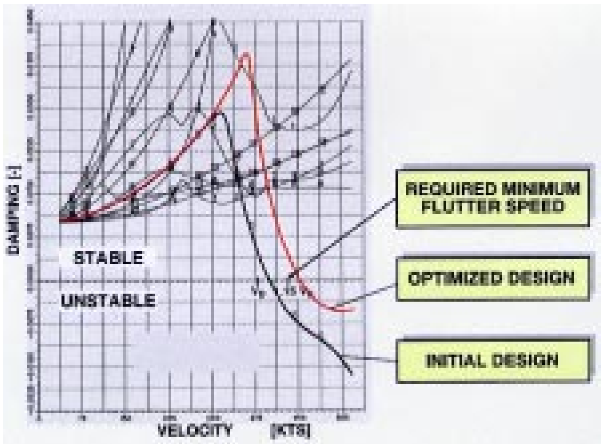

Fig. 3: Flutter Speed Increase (Ref. 1)

Similar „repair solutions“ are used for improving aeroelastic effectivenesses of lifting surfaces. Knowledge of structural bending-twist coupling, i.e. observation of the physical behavior of the structure, may be used to manipulate the stiffness distribution appropriately[4]. However, interactions between different aeroelastic requirements are not obvious. An example from the above-mentioned MDO-Project shows that wing optimization with aileron effectiveness constraints may have a noticable effect on the symmetric trim of large jet transport aircraft. Hence, cross-couplings between symmetric and antimetric load cases, boundary conditions, and design requirements exist. Again, limitations of current optimization packages often prohibit simultaneous consideration of constraints from different boundary conditions.

Servoelastic Aspects for High Performance Aircraft Design

The integration of modern electronic flight control systems (EFCS) in combination with fly-by-wire technology offer the design engineers a chance to implement additional active control functions in order to gain benefits for the airframe performance. The interaction between the aircraft's flight control and additional active functions has emerged as an important design potential. This field of merging the disciplines structural dynamics, aeroelastic and flight control system dynamics is called aeroservoelasticity. The interactions are illustrated in Fig. 4.

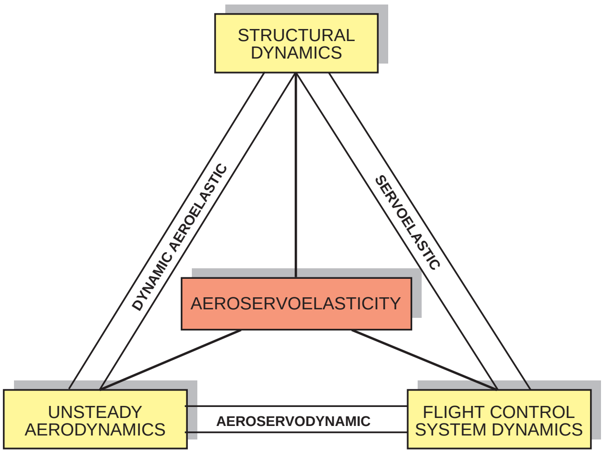

Fig. 4: Aeroervoelastic Triangle

In the aeroservoelastic triangle, the left leg represents the dynamic aeroelastic interaction which does not include inputs from an active system. Similarly, the lower leg of the triangle stands for classical aeroservodynamic control system synthesis. Finally, the right leg depicts the important dynamic servoelastic coupling between the elastic modes of the aircraft and the active control system. This coupling, together with the unsteady aerodynamic feedback inputs from servo-actuated active control surfaces, then results in an aeroservoelastic interaction which is generally known as „structural coupling" and can be as dangerous as flutter. To avoid dangerous instabilities aeroservoelastic design criteria have been developed for active control functions which take into account flight dynamics, structural stability, and performance as well.

All active functions (control systems) have to be designed to cover full rigid and flexible aircraft frequency ranges with respect to the aircraft rigid mode and structural mode coupling stability requirements for each control system loop. The structural coupling influences will be minimized by notch filters or other measures and the control system must be as robust as possible with regard to all aircraft configurations and to all kinds of non-linearities of the complete system „flying aircraft with active controls".

Additional requirements to be met within the design process are:

- minimization of impact on actuator fatigue
- minimization of impact on actuator back-up structures fatigue life to reduce weight penalties

The most important active control functions which are mature for implementation are:

- care-free handling
- Maneuver Load Control (MLC)
- Gust Load Alleviation (GLA)
- Fatigue Life Enhancement
- Deformation and Elastic Mode Control
- Flutter Suppression
- Ride Comfort Improvement

The first experimental applications of these functions have been repair solutions in most cases to meet aircraft performance specifications. The full potential of this technology however can only be explored when it is used as design tool and fully integrated into the MDO process of active aircraft structures.

At present the aeroelastic design of active aircraft structures is still the task of the future. Currently, only a patchwork of methods is available:

Active flutter suppression and gust alleviation have matured from an academic to almost an industrial application level[5]. In case of a controller failure, however, current certification procedures require an actively controlled aircraft to be dynamically stable with the same, significant safety margins as a purely passively controlled aircraft. Significant structural weight reductions from exploitation of active flutter suppression can therefore not be expected. It might pay off if the common 20% dive speed to flutter speed margin is valid for *actively* flutter-suppressed aircraft, but a reduced safety margin is accepted in the case of flutter suppression controller failure.

The EFCS is usually designed and optimized for flight-dynamic stability and performance with well-established methods. The aircraft model in these methods is derived from rigid structure properties using aeroelastic efficiencies. Since the actual aircraft properties differ from those assumed in the model - in flexibility and dynamic behavior - expensive and time-consuming adjustments are necessary. Seyffarth et. al.[6] suggest a two-step procedure to correct this discrepancy. First, sensor locations, sensor attachments, actuator transfer functions, and control surface dynamic properties are optimized. Second, notch filters and phase advance filters are designed to eliminate sensor signals from structural vibrations which could affect EFCS performance and stability. This design task is in itself a challenging optimization problem, as multiple loading and flight conditions must be considered[7].

This traditional separation between low- and high frequency behavior, EFCS and structural design decomposes the design problem into manageable, discipline-conform sub-tasks, but also poses a number of costly integration challenges.

Taking into account that computational power doubles per year new approaches to an integrated flight control design and optimization with respect to flight dynamics, active functions and aeroelastic stability requirements seem to become feasible. High performance computing will not only speed up the MDO process, it will start with better aircraft models and will allow the representation of multiple boundary conditions in an „integrated MDO process".

Previous Aeroelastic Optimization Applications, Development Trends, and Technology Gaps

Table 1 provides an overview of some published DASA-M studies in the field of aeroelasticity which referred to identified shortcomings in the area of aeroelastic optimization at the time of their completion. The table is not meant to provide a summary of these studies, but a condensed account of information pertaining to the topic of this paper. The interested reader is referred to the original papers for details. The following section summarizes technology gaps which were identified in the course of these studies, outlines actions taken to close these gaps, and identifies current trends in the development of aeroelastic optimization capabilities.

Selected activities in the 1980s focused on identifying and solving stability problems encountered with existing designs. Flight testing of a 1/3 scale model of the SB-13 tailless glider airplane revealed a severe low-speed instability[8]. The problem was analytically traced back to coupling between the aircraft's short period oscillation and the first symmetric wing bending mode. One approach to alleviation of the instability was to use structural optimization. Limitations of the programs TSO and FASTOP, however, made modeling of this coupled flight dynamic/structural elasticity problem very difficult. It was concluded that flight dynamics must be integrated in aeroelastic optimization software.

In 1986, transonic wind tunnel tests were used to validate composite fin designs obtained from structural optimization[9]. In static aeroelasticity and flight dynamics commonly a linear dependency between a given aerodynamic load coefficient and a control surface deflection is assumed. This assumption is the basis of the notion of aeroelastic effectiveness, a constant factor representing the ratio of a given aerodynamic load coefficient achieved by a flexible structure compared to that of a rigid structure. This wind tunnel test, however, showed a non-linear relationship between rudder twist and stagnation pressure. The phenomenon was traced back to geometric coupling of rudder deflection and load-induced fin box deformation. Hence, flight dynamic calculations considering structural flexibility in form of stagnation pressure independent effectiveness values may be unreliable, and trimmed aeroelastic equilibrium load calculations are required.

As seen from these two examples, early studies attempting to avoid aeroelastic stability problems by automatic computational design revealed that the state-of-the-art optimization tools of that time lacked several important analysis and modeling features. Structural analysis programs, on the other hand, did not have the desired open, multidisciplinary optimization features. In order to satisfy both needs, the package LAGRANGE[10] was developed at DASA-M. As a structural optimization utility by design it includes both FE-based analysis capabilities and optimization features, for example a host of optimization algorithms and analytical sensitivity calculation for a number of constraints.

The software was successfully applied to optimization problems throughout the 1990s. One of the first applications was weight minimization of the above-mentioned small, simplified ACA-Fin model subject to strength, aeroelastic effectiveness, flutter and gauge constraints[11]. Based on success with existing analysis capabilities, additional desirable features were formulated (refer to the „Technology Gap" column of Table 1, third entry from above). Among these were buckling constraints, which were hence introduced into LAGRANGE.

A larger example was optimization of the X-31A composite wing, which already considered buckling in addition to strength, effectiveness, and flutter constraints[12]. The resulting ply orientations, however, were not suited for composite manufacturing. The concept of Constructive Design Elements was therefore introduced in LAGRANGE to allow addition of tape laying constraints[13] and shape variables, for example for optimal stringer placement in composite panels under buckling loads[14].

Entire aircraft were also modeled and optimized. The JPATS contender „Ranger 2000" in 1994[15] was checked in preliminary design for aeroelastic stability, and the potential for control surface flutter was detected. The problem was solved by positioning masses on the control surfaces. The mass values were then optimized with LAGRANGE.

The largest application yet was a Stealth Demonstrator model to be optimized for minimum weight subject to strength, buckling, effectiveness, and flutter constraints[3]. In order to consider ten symmetric and antimetric load cases simultaneously, a full model had to be used. With 22,000 degrees of freedom, 11,000 structural elements, 360 design variables and 110,000 constraints the problem was at the limits of reasonable size with respect to run time and the possibility of physical interpretation. The need for techniques to solve such tasks with reduced (half-) models and multiple boundary conditions is obvious.

A 1992 study with the ACA-Fin[16] showed that constraints like buckling may complicate the structural design space significantly. In such a case the choice of optimizer (or a sequence of optimizers) determines whether an optimum, or even a feasible design, can be found. To date, algorithms suitable for buckling problems are still sought.

By the mid-1990s, LAGRANGE had been used to solve most traditional aeroelastic optimization problems using Doublet-Lattice-Method aerodynamics with sizing, shape, and fiber orientation design variables. At the same time, the need for integration of structural optimization, aerodynamic analysis and optimization, flight dynamics and control systems design became a pressing issue. With regard to jig shape, deformed aircraft drag, and flexible aircraft flight dynamics, aerodynamic methods at least comparable in fidelity to those used in preliminary aerodynamic design were required for aeroelastic computations. Furthermore, the capability to alter the global structural layout numerically was desired so that structural data could be quickly generated in response to changes in aircraft configuration - like in the course of wing planform optimization. Further extensions of LAGRANGE were considered to be prohibitively complex and costly, and efforts were made to use the system as a stand-alone component either in tight coupling with a few other disciplinary tools, or loose coupling within larger, more general architectures.

With regard to aeroelastic modeling, tight coupling of LAGRANGE with a higher order panel method, HISSS[17], is about to be completed. This combination allows accurate load modeling at given trim conditions. Optimization control remains with LAGRANGE; it communicates with a stand-alone coupling component via shared memory and inter-process control.

LAGRANGE already supplied sensitivity information in a 1991 study on integrated aerodynamic, flight dynamic, and structural design of the ACA-Fin[18]. Models of four planform variants were generated manually and the sensitivity of aeroelastic side force effectiveness with respect to taper ratio, aspect ratio, and area were calculated. These data were then inserted into the Global Sensitivity Equation, GSE, for derivatives of side force coefficient (flight dynamics), side force (aerodynamics), and effectiveness (structures). Due to the lack of a software framework supporting loosely-coupled, GSE-based algorithms at that time, global sensitivities were used to determine new candidate configurations, but not to drive an automatic optimization.

In the MDO-Project[2,19] an automatic model generator was developed and proved to be very useful for rapid variant generation for large transport aircraft wings. In one demonstration application of the program suite, a two-level weight minimization was implemented with structural sizing variables at the lower level using LAGRANGE, and planform variables at the top level controlled by the MDO framework tool iSIGHT[20], which had become available since the 1991 ACA-Fin study. The FE models for LAGRANGE were produced by the model generator. Experience with this tool also underscored how important it will be to develop future generators which are applicable to generic wing-type components (transport, fighter, tail, etc.) and multiple structural concepts, and ensure robustness with regard to model degeneration. Similar modules are required for other structural components.

In another task of this project, it was necessary to combine the specific capabilities of the aeroservoelastic optimization tool, AIDIA, at Aermacchi in Italy, with those of LAGRANGE at

DASA-M in Germany. A simple approximation-based approach was used for this particular multi-site problem[19]. Approximations of flutter constraints on one hand, and weight, stress constraints and aeroelastic effectiveness constraints on the other hand as functions of sizing variables were generated from data produced during optimization studies at Aermacchi and DASA-M, respectively. These approximations were then integrated into iSIGHT, and a design satisfying both sets of constraints approximately was found. The availability of a framework tool facilitated implementation of this method. For future studies it is desirable to have off-the-shelve software for generating multi-dimensional function approximations of several types, too.

This review indicates that until a few years ago the focus of in-house developments was on improvement of disciplinary analyses and integration of new constraint types in a tightly coupled optimization package. More recently, the need to combine existing disciplinary analysis capabilities in order to solve multi-discipline design problems shifted interest towards tight coupling between specific analysis tools where appropriate and possible. Also due to growing acceptance of MDO ideas in the company, lose coupling via standard interfaces, controlled by framework software is planned and tested for the general case. Important pieces are still missing for industrial application: Software for supporting generic model generation, software for design space approximation, MDO methods for multi-site, multi-partner problems, and a product/process data standard to allow standardization of disciplinary tool interfaces, to name a few.

Future Industrial User Requirements

In order to provide a comprehensive picture of future trends in aeroelastic structural design and user requirements, a catalogue of questions prepared by Mr. Joe Giesing of McDonnell Douglas Corporation was presented to seven DASA-M staff members in the field of aerodynamics and structural dynamics, ranging from disciplinary experts to technical managers. Questions and answers are listed in Tables 2 and 3. The following paragraphs represent a summary of all responses. Question numbers refer to the order used in Tables 2 and 3.

Major barriers to MDO in industry (question 1) are, in the field of structural optimization, the lack of optimization algorithms for topology/layout/material distribution, and Mathematical Programming (MP) tools for dual formulations. Most MDO technologies still not mature enough for industrial application, or have not been implemented in mature software products. Integration of disciplinary analyses is difficult since tool interfaces do not match (see also question 5). Organizational and cultural aspects are an important factor, since the concurrent nature of MDO processes differs significantly from the traditional sequential practice. No coordinating position for MDO is present in typical industrial hierarchies.

The typical design problem (question 2) is to find a feasible, better, or locally optimal design in a mostly continuous design space. The global optimum is of lesser interest.

Current software integration tools (question 3) have only recently been used in MDO applications. Improved support of design process organization and graphic visualization is required. The latter refers specifically to monitoring of optimization progress which lends itself to physical interpretation and identification of typical features of a family of designs.

The most significant *integrated simulation challenge* (question 4) is nonlinear, aeroelastic, trimmed load calculation. The next important step will be inclusion of EFCS design for fully integrated loads and performance calculation. Current practical challenges are handling of multiple design configurations in load calculation, and consideration of manufacturing aspects like tape steering in composite design.

Five *barriers for using disciplinary analysis processes in MDO and design* (question 5) were mentioned: Tool robustness, automation level, ease of use and checking, lack of control by experts, and lack of interfaces to other disciplines. The last item includes both consideration of other discipline's needs and data format compatibility. Since optimization is also considered a disciplinary analysis, another problem is the reliability of current MP tools.

Tightly coupled methods for solution of integrated simulation problems (question 6) are needed for specific problems with strong or high data volume couplings. Loose coupling is preferred though, since the systems are more transparent and flexible.

Analytical sensitivity derivatives are used within LAGRANGE, and the current challenge is to integrate this package and other disciplinary tools. *Sensitivity derivatives* for existing tools (question 7) are therefore not if immediate interest.

Automatic differentiation tools (question 8) will most probably not be used in-house. It is more likely that this work will be contracted to academia or research laboratories.

The *most important obstacles for using optimization* (question 9) are user familiarity/training and difficulty in interpreting results. Improved graphical monitoring tools would facilitate interpretation (see question 3). A cultural aspect is that optimization is considered to be time consuming, so that in considering product cost vs. possible product improvement the management go-ahead for efficient optimization often comes too late.

The primary reason for not using *decomposition-based optimization algorithms* (question 10) is the lack of demonstrated and validated software packages. Furthermore, an efficient implementation of such concurrent design methods faces organizational obstacles (see also question 1).

In the previous paragraphs, responses were listed irrespective of the questioned persons' backgrounds and positions, although the individual perspectives definitely permeate the responses. Staff members involved in the actual computational work are primarily concerned with practical issues like handling of current tools (analysis and optimization alike), solution of aeroelastic simulation problems today or in the near future, disciplinary tool coupling, and interpretation of results. Responses of individuals in charge of project and department management focus on topics like decomposition techniques or design process organization, and organizational challenges impeding MDO implementation in industry. This polarization is most obvious in answers to the last question asking for *the three MDO developments which would facilitate the designer's job over the next 10 years* (question 11). Assuming that the term „MDO developments" refers strictly to general-purpose MDO algorithms, methods, and implementations, then the following items can be extracted:

- reliable, demonstrated, and validated software packages for industrial-size applications of MDO algorithms from conceptual to detailed design, including graphical monitoring, design space approximation, multi-criteria decision making, and analysis integration tools;
- standardized tool interfaces and disciplinary analysis tools which are developed with interdisciplinary interfacing in mind; this requires identification of each single discipline's (or tool class's) required inputs and generated outputs;
- MDO algorithms suited for optimization tasks to be performed by heterogeneous industrial consortia.

Organizational aspects do not fit within this strict definition, but are nevertheless very important. The answers reflect the opinion that multi-discipline and concurrent design thinking is not manifested in today's industrial design processes and company structures.

Summary

The need for increasing integration of aerodynamics, structures, and control system design in a Multidisciplinary Optimization environment is evident both from past design trends and industrial user predictions of future directions.

The most pressing issue for the structural designer's daily work is the gap in fidelity between aerodynamics used in performance calculations, flight dynamics and aeroelasticity. Generic flow-structure interaction techniques are needed so that Euler and Navier-Stokes Methods can be used in early design for reliable load and maneuver performance predictions. High performance/parallel computing will enable practical use of these methods.

In the very near future, however, loosely coupled MDO strategies will be used in the industrial environment. Software framework tools supporting these approaches exist but need to be refined, extended, and validated for productive application. Reliable, robust software for generic model and design space approximation is missing. When this is accomplished, MDO methods like Concurrent Subspace Optimization need to prove applicability to industrial use. Successful implementation might be the key to the required cultural change in industry towards concurrent engineering.

Model	Task	Method	Key Finding	Conclusion	Technology Gap
SB 13 (1985)[8]	eliminate flutter within flight envelope	manual optimization/ trend studies with TSO/FASTOP	flutter source: coupling of first elastic symmetric wing and short period mode	need to change material, spar position and wing planform	aeroelasticity - flight dynamics coupling
ACA-Fin (1986)[9]	validation of optimized composite designs	wind tunnel tests	nonlinear relationship between rudder command and load due to structural deflections	traditional design for "effectiveness" possibly unreliable	aeroelastic equilibrium load calculation
ACA-Fin (1990)[11]	weight optimization with strength, aileron effectiveness, flutter, minimum gauge constraints; design variables: composite ply thicknesses	optimization with LAGRANGE			efficient methods for cross-discipline sensitivities and app. optimization procedures; modeling: FCS, aeroelastic equilibrium and thermal loads, buckling, dynamic response; fiber orientation, spar positioning; multi-objective optimization
ACA-Fin (1991)[18]	integrated planform & sizing optimization for flight dynamic and stress requirements	total sensitivity analysis using 3x3 GSE (flight dynamics, aerodynamics, aeroelasticity)	transparency of GSE: automated procedure reflects well-known couplings in process structure	GSE useful for more complex problems	optimization proc. using GSE; applicability of existing software to integrated optimization
ACA-Fin (1992)[16]	1. buckling influence 2. performance of different optimization algorithms	optimization with LAGRANGE	1. buckling is design driver; 2. most algorithms find only *closest* local optimum	1. buckling must be considered; 2. sequence of optimizers necessary	suitable optimization algorithms for buckling problems
X-31A (1990)[12]	minimize weight s.t. buckling, stress, effectiveness, flutter	optimization with LAGRANGE, material tests	optimal design not suited for manufacturing		composite materials manufacturing constraint modeling
Ranger 2000 (1994)[15]	alleviate flutter tendency in preliminary design	optimization with LAGRANGE; flutter flight test; ground resonance test	mass positioning on control surfaces more efficient than struct. reinforcement		
Stealth Demonstrator (1995)[3]	minimize weight s.t. strength, buckling, aeroelasticity; symmetric and antimetric loading	optimization with full model in LAGRANGE	sequence of algorithms successful; structural model very large (cycle time)	large optimization problems can be handled	simultaneous consideration of multiple boundary conditions with half models
„MDO-Aircraft“ (1998)[19]	1. optimize wing box structure (sizing variables) subject to static and dynamic aeroservoelastic constraints at different sites 2. test MDO methods and framework tools	development of MDO coordination method based on sub-problem approximations; application using MDO framework tool; optimization with LAGRANGE (stress and effectiveness constraints)	1. leads to acceptable global design if app. are good; partner studies yield hints at location of global solution 2. tightly and loosely coupled methods required depending on design stage	no weight savings from active flutter suppression under current regulations; sensor location & actuation system parameters needed as design variables; interaction between roll effectiveness and symmetric trim	suitable MDO method; automated, generic, robust model generation; product/ process data standard; approximation generation software; aeroelastic effects in performance and flight dynamics

currently still open technology gaps are underscored

Table 1: Aeroelastic Optimization Applications and Conclusions

1. What are the major barriers and challenges to MDO in industry? Do they pertain to the state of the art in computer sciences, the availability of a suite of robust, automated analyses of varied accuracy, the need for robust optimization algorithms and tools, or the organizational (cultural) challenges you are facing?	SO industrial processes in companies are sequential; MDO requires more concurrent engineering processes; tool interfaces do not match; MDO technologies not yet available for industrial use (maturity); no coordinating function (persons) for MDO in industry SO lack of general MP tools on dual formulations; lack of topology/ layout/material distribution algorithms MO organizational/cultural: acceptance of MDO by discipline experts and management
2. What is your design problem and design goal? For example, is your goal a better design or the best design? Do you want the code to find the optimum or just show you the design space? Is your optimization mostly continuous or mostly discrete? Do you have multiple objectives to maximize?	SO to get a feasible design is most important A multi-point design: feasibility, reliability DE to get a better design SO to find the nearest local optimum; variables: mostly continuous (MP algorithm for discrete variables desirable for composites) MO to find a feasible, better design in a mostly con tinuous design space with a large number of design variables and constraints and multiple objectives AEO reduced time (model generation, results evaluation); include all design drivers; discover critical aspects early; model close to manufacturing (affordability, final weight); continuous process from definition to product
3. Has the current state of software integration tools helped your implementation of integrated design and analysis processes? Do these processes require more than your current software tools can deliver in: Database management; distributed computing; analysis and design graphic visualization; analysis and design process organization, integration, monitoring and control	SO analysis and design process organization A expert systems for guidance and easy implementation of new applications/analysis tools; multi-criteria decision making tools DE all items SO all items MO in decreasing order of importance: analysis and design process organization, graphic visualization (monitoring!) SD visualization/monitoring: extraction of characteristic features of a family of designs
4. There is significant research nowadays directed to, for example, the multidisciplinary simulation for aeroelastic, fully nonlinear, multiple control surface, trimmed load calculation. Do you frequently encounter different integrated simulation challenges which you believe require additional research and development?	SO integration of FCS design and structural dynamics (including aeroelastics and flight dynamics) A virtual aircraft in full flight SO tape steering subject to manufacturing aspects AEO multiple configurations (fuel, stores, actuator failure modes)
5. What are the major barriers in the use of disciplinary analysis processes in MDO and design? Consider the following areas: Cycle time, automation, robustness, fidelity, ease of use and checking, and applicability for MDO, loss of control by technical experts, or other.	SO robustness, usability and applicability for MDO, tool interfaces DE automation, ease of use and c hecking SO in decreasing order of importance: robustness, loss of control by technical experts, ease of use/checking, reliability of MP tools MO in decreasing order of importance: applicability to MDO (interfaces), loss of control, ease of use AEO single discipline models too complex, not considering other disciplines' requirements (e.g. statics FEM: wing mass, stiffness, DOFs); lack of understanding other disciplines' needs
6. One can solve integrated analysis and simulation problems using either a tightly coupled or a loosely coupled approach. A tightly coupled approach is a very efficient method but somewhat monolithic and it requires a new simulation code development. Instead, the loosely coupled approach is less efficient, but more modular and requires the integration of existing simulation codes. Most, if not all integrated analysis and simulation problems in place nowadays are of the loosely coupled variety. Would you consider the use of a tightly coupled method?	SO loosely preferred due to complexit y of tightly coupled systems A loosely coupled: allows for easily exchanging analysis tools SO both is needed! MO tightly coupled only for special problems (with strong coupling); loosely coupled preferred due to flexibility

SO department manager, MDO expert
A R&D project manager, aerodynamicist
DE conceptual designer
SO structural optimization expert
MO MDO expert, aeroelastician
AEO aeroelastician, structural optimization expert
SD structural dynamicist

Table 2: Responses to „MDO Requirements" Questionnaire (1)

7. Sensitivity derivatives are available for a number of commercial and government-supplied simulation codes. Are there other simulations for which you wish you had sensitivity derivatives? Also, would you consider using that information even in other than an optimization setting? If so, do you have specific requirements on such sensitivity capabilities?	
8. Are you likely to invest time and effort as a user of automatic differentiation tools to produce your own sensitivity analysis software or are you looking to academia/ government researchers to use those tools and generate sensitivity analysis software for your use?	SO academia/labs SO academia/labs MO academia/labs
9. What are the single most important obstacles to your use of optimization? User familiarity and training, optimization code performance, reliability/robustness, ease of use, difficulty in formulating an optimization problem representative of the design problems you face in your day-to-day applications, difficulty in interpreting the resulting designs or in validating them, or other?	SO user familiarity and training SO performance, reliability/robustness, difficulty in interpreting/ validating results AEO management go-ahead for efficient optimization often comes too late; external opinion: optimization costly, increases product cost ("... for a 1% weight saving")
10. Few, if any of the currently available multilevel/multidisciplinary (CSSO, CO...) optimization algorithms based on decomposition have been used in industry. Do you attribute that to: The fact that one does not need in reality such general purpose methods, the complexity of the methods, the lack of maturity of the methods, or the lack of demonstrated and validated software packages?	SO lack of demonstrated and validated software packages MO too complex/immature for industrial applications, also hardly known or understood (organizational aspects); lack of software
11. In order of decreasing priority, what are the 3 MD developments which would help you do your job better, as a designer over the next 10 years?	SO 1. process and company organization; 2. standardized tool interfaces; 3. demonstrated and validated MDO software packages A optimization strategies for heterogeneous projects (with partners from various industry branches) SO 1. conceptual design optimization tools; 2. more general MP tools; 3. easy-to-use monitoring tools MO 1. product/process model standard (data format) and interfaces catering to it; 2. software (MDO algorithms, approximations); 3. MDO strategies for multi-partner, multi-site optimization AEO 1. completeness of single-disciplines' „set-of-needs " (automatic, integrated load case generation); 2. efficient aero-structures coupling mechanisms (generation, reliability, modifications); 3. formulation of active a/c optimization approach: *What is the optimum deformed structure shape? How can it be achieved at minimum „cost" (energy, mass of actuation system)? What is the optimum passive structure and control system design to achieve an overall optimum design?*

SO department manager, MDO expert
A R&D project manager, aerodynamicist
DE conceptual designer
SO structural optimization expert
MO MDO expert, aeroelastician
AEO aeroelastician, structural optimization expert
SD structural dynamicist

Table 3: Responses to „MDO Requirements" Questionnaire (2)

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